

# **Coherent Path Beamformer Front End For High Performance Acoustic Modems**

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## **LONG-TERM GOALS**

The long-term objective is a smart acoustic network for multiple Autonomous Underwater Vehicles (AUV) operation, with integrated communication and positioning capability. To do so, a new generation of Coherent Path Beamformer (CPB) will act as a network decoder and arbitrator for data communication and long (short) base line. Also, wireless communication to shore would be available for control and real-time data transfer. Finally, the AUV's will be carrying an improved version of the compact low-cost Acoustic Modem. This will require extensive research and testings of our adaptive beamformer "front-end", now built and tested in the ocean. An adaptive coherent filtering process is being developed to decode information transmitted at high data rate (exceeding 16kbps) in very shallow water, suitable for transmission of image information from AUV's. As a second but equally important long term goal, based on experimental data, is to obtain a better understanding of environmental acoustics related to information transmission underwater. This knowledge will be used to develop a test model for evaluating under water acoustic modem and other shallow water sonar system performance.

## **OBJECTIVES**

Our Scientific objectives in this effort are to conduct at sea acoustic transmission experiments at frequencies from 16kHz to 32kHz, using a 32 by 32 Mills-Cross array and a single-channel acoustic modem. The intents are to measure and characterize the underwater acoustic channel, receive data collected by the AUV's, remotely control and monitor multiple AUV's during at sea operation. We are also using the experimental data to evaluate the performance of the Coherent Path Beamformer in very shallow water and highly reverberant environment. These results are also being used to develop a low-cost, high-reliability beamformer modem/long-base-line combination for use by the AUV's.

## **APPROACH**

The underwater acoustic channel is characterized by strong time varying multipath conditions. To some degree, each path is independently time delayed and frequency smeared by fluctuations induced by surface and internal waves, turbulence, temperature gradients and other related phenomena. The extent and the independence of these variations place a theoretical upper bound on the information transfer rate in such a medium. In addition to direct multipath, bistatic volume and boundary reverberation from distributed scatterers in the surrounding water column, sea floor and sea surface make it even more difficult to communicate at high baud rate in shallow water. Our strategy is to

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separate communication systems based on their application. To be more specific, two systems have been developed:

- 1) The Coherent Path Beamformer is a high-performance communication receiver (uplink) using Phase Shift Key processing for high data transfer rate at long distance and in very shallow water. It is mainly used for data transmission at the present time, but also has a very strong potential in network applications. The source is usually installed under a boat or an AUV.
- 2) The general purpose Acoustic Modem is a low-cost and very compact transmit/receive system for lower data transfer rate, based on Multi Frequency Shift Key (MFSK) processing technique. Very robust, it is used for command, navigation and networking, and is currently installed in every AUV OEX.

The method of separating signals received by an acoustic array into statistically uncorrelated components (Principal Components) is developed by LeBlanc, and presented in a paper "Angular-Spectral Decomposition Beamforming for Acoustic Arrays". Briefly, the Principal Component Beamformer is an array time series data reduction method that allows one to observe the statistically uncorrelated components of wave energy arriving at an array of acoustic sensors. In the Coherent Path Beamformer output, each channel represents a vertical beam that is focused in the direction of the collection of correlated spatially coherent energy arriving at the array of acoustic sensors. Nulls are pointed in the direction of the remaining other acoustic incoherent paths therefore canceling interference within the principal beam. The advantage of this approach is that it provides separation between the various incoherent multipaths arriving at the array. In this manner, the Doppler component of a single acoustic path can be effectively removed from the time series data. Another important advantage of the CPB approach is that it provides automatic tracking of the acoustic transmission source and a spatial signal processing gain. Thus, in addition to nulling out interference, the beam pattern of the CPB rejects reverberation and ambient noise. Finally, any remaining interference may be reduced using adaptive equalization. In developing the CPB, we have found that it is not necessary to update the CPB coefficients over the entire information packet, thus reducing the computations required to process the message. This holds true for message lengths of under a few seconds. By combining multiple Coherent Path Beamformers combined with resampling techniques and Maximum Likelihood Detection, high data transfer rates can be achieved, as shown in the following two sections.

## **WORK COMPLETED**

Two systems have been developed in the Sonar Laboratory of Ocean Engineering. The first system, called Coherent Path Beamformer (CPB), or MillsCross, is a high-performance communication receiver for high data transfer rate at long distance and in very shallow water. The second system, called General Purpose Acoustic Modem (GPM) is a low-cost and very compact transmit/receive system for lower data transfer rate. Very robust and compact, it is used for command, navigation and networking, and is currently installed in every AUV OEX.

Both MillsCross and General Purpose Modem have been successfully tested at sea using two boats, as depicted in Figure 2. Figures 3 and 4 show the MillsCross and the Modem, respectfully. The concrete slabs for each system have also been deployed in the location planned. Data have been collected from April to September 1999, and a report on communication performance is in process. Both MillsCross and GPM fulfill their expected functions, which are given in table 1.

The SFOMC Shallow Water MUX experiment is the first long-range experiment scheduled for the MillsCross. The idea is to attach the MillsCross and a General Purpose Modem (GPM) to an underwater Multiplexer (MUX) controlled from shore through fiber optics (Figure 1). Many other systems are involved in this experiment. Later on, the AUV OEX's should be deployed to test the new docking station. The water depth is ranging from 10' to 30'. The General Purpose Modem has the following characteristics:

- 1) Controlled through LonWorks and RS422 by host computer on shore.
- 2) Reprogrammable from shore.
- 3) Can be used as a standard MFSK modem in acoustic network.
- 4) Can transmit PSK sequences to the Millscross.

The Millscross operates as follows:

- 1) Controlled through Ethernet by host computer on shore.
- 2) Waits for a trigger to start recording sequence.
- 3) Records filtered and decimated data on disk.
- 4) Transfers data upon request to shore.

The major effort going forward is software development and data analysis:

- 1) Space-Time analysis of acoustic channel.
- 2) Doppler spread study of the acoustic channel.
- 3) Study of acoustic channel capacity for communication.
- 4) Data Transmission Protocol for Maximum Performance.

At the present time, the MUX is not able to provide neither the minimum 10Mbps nor the more practical dedicated 100Mbps Ethernet required for at-sea operation. Once this issue will be solved, we will proceed as scheduled.

As for the low-cost MFSK modem, the following tasks have been completed:

- 1) An upgrade of the previous stand-alone Innovative Integration DSP board has been installed.
- 2) More performant variable gain preamplifiers have been installed and the software updated for a better control of the dynamic range.
- 3) An improved single-channel transducer is now used on every modem. The major differences with the previous model are a much improved hydrodynamic shape and a more uniform response in the 15 kHz to 35 kHz bandwidth.
- 4) The modem-host interface has been fine tuned, in the field of data handling routines to use linked list based queues, and hardware/software support for data flow control.
- 5) The MFSK modem now uses optimized Viterbi and dual Viterbi/BCH as error correcting schemes.
- 6) A data storage mode has been added for off-line signal processing.
- 7) The MFSK modem can now be reprogrammed over a 3 wire interface, and it can burn its own flash memory.
- 8) A Graphic User Interface has been written for test control including plots for ambient noise and spectrum utilization.

## RESULTS

The MillsCross/Coherent Path Beamformer has been successfully tested at sea in multiple occasions between April 1999 and August 1999. Since then, our efforts have been focused on data analysis. Table 2 gives a list of the different transmission modes tested at sea, while table 3 gives a list of the results currently available. More results will be given in conference for early year 2000 (most likely Oceanology 2000, Brighton, UK).

Figure 2 depicts a typical experiment, while Figure 3 and Figure 4 contain pictures of the receiver and source, respectively. The data were transmitted using a standard AUV modem towed by a boat moving in a zig-zag pattern within a 120 degrees cone, at distances from 1km to 1.5 km. Boat speed ranged from 0 to 5 knots (speed over ground). Wave height ranged between 1'-2' and 4'-5' depending on the day. Water depth ranged between 25' and 45', which can be considered as very shallow water. The various data sets have been collected along the coast of Port Everglades, notorious for its highly reflective bottom (sand, crystals and reefs) and its heavy boat traffic. The ambient noise Power Spectral Density was around 70dB/Hz, and the reverberation time varied between 35ms and 60ms. In other terms, ambient noise and multipaths were as bad as they can get for Coherent Phase Shift Key communication.

Figure 5 shows a message packet received on a single channel. The data, coded using BPSK and 16kHz of bandwidth, are transmitted at 16,000 bps of burst rate. Over 35ms of significant multipath clearly shows, corresponding to 500 symbols. After using the a single Coherent Path Beamformer, the same data show about 2.5ms of significant multipath, or 40 symbols. The measured Signal-to-Noise Ratio (SNR) at 1.2km exceeds 29 dB. In the case of BPSK and QPSK, the minimum SNR to obtain reasonable probability of error for BPSK is around 10 to 11dB, proving that the MillsCross/CPB should perform well at ranges up to 10km at 16,000 bps of burst rate.

The FSK acoustic modem was successfully tested in various conditions in order to evaluate the overall robustness of the system. Typically, the modem was deployed at mid-depth in 30 to 100 feet of water in the ocean. The large amount of background noise (90 dB re 1 uPa) and important reverberation times provide a challenging testing environment. Using a low baud rate, the modem relies on time and frequency diversity to improve reliability when a transmission speed is not a priority.

The modem can work in four different modes (sending packets of 3, 6, 12 or 16 bits at a time) and three different error correcting codes (BCH, Viterbi and dual BCH/Viterbi) have been implemented. Higher transmission modes provide higher baud rate (up to 2400 bps) in friendly environments but are less susceptible to work properly in adverse environments. The lowest mode (220 bps) has been extensively tested and typically provides 100 dB of SNR at a range of 100 m, with a typical maximum range of operation of 2 km. While increasing the distance between two modems, signal power was found to decrease according to predictions (assuming spherical spreading). The value of error correction coding was demonstrated by witnessing an increase in the amount of corrected bits with increasing distance. A performance chart is given in Figure 7.

## IMPACT/APPLICATIONS

Experimental results are providing a new insight to the understanding of how shallow water propagation conditions affect the information capacity of digital data transmission for sonar operating in the frequency range of 25 kHz. Hundreds of kilobytes of test data encoded using Phase-Shift-Key and

multiple pulse (symbol) length have been transmitted at distances exceeding a kilometer over a moving platform. This is helping to establish error rates, adaptation time constants, and the influence of the environment on the stability of the various modes of propagation. Principal component analysis of the received data using moving platforms has also provided an important insight into the frequency smear of each of the various multipath receptions. This information is invaluable in generating models for use in testing acoustic modem designs and high-rate data transmission in shallow water environment.

The MFSK modem proves that use of multiple frequency channels and frequency-hopping technique are adapted for multiple-users underwater communication. The fusion between both techniques (PSK and MFSK) is the next step for a fast and highly reliable underwater acoustic network.

## **TRANSITIONS**

The low-cost single channel modem that uses Gaussian spread spectrum wavelets with compensation and the associated hardware has been successfully transitioned to a commercial oceanographic instrumentation company: Edgetech Inc. is currently manufacturing modems.

## **RELATED PROJECTS**

The Coherent Path Beamformer project has two important objectives: High bandwidth underwater acoustic communication, and the development of a tool for obtaining a better understanding of the underwater acoustic channel in shallow water. Success in these objectives will be extremely beneficial to other projects in the ONR AOSN effort as well as other Navy objectives in shallow water acoustics.

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Function	General Purpose Modem	MillsCross
Ethernet	None	100Mbps and 10Mbps
Serial	RS422	None
LonWorks	78kbps	78kbps
Average Power Consumption	25 Watts	99 Watts

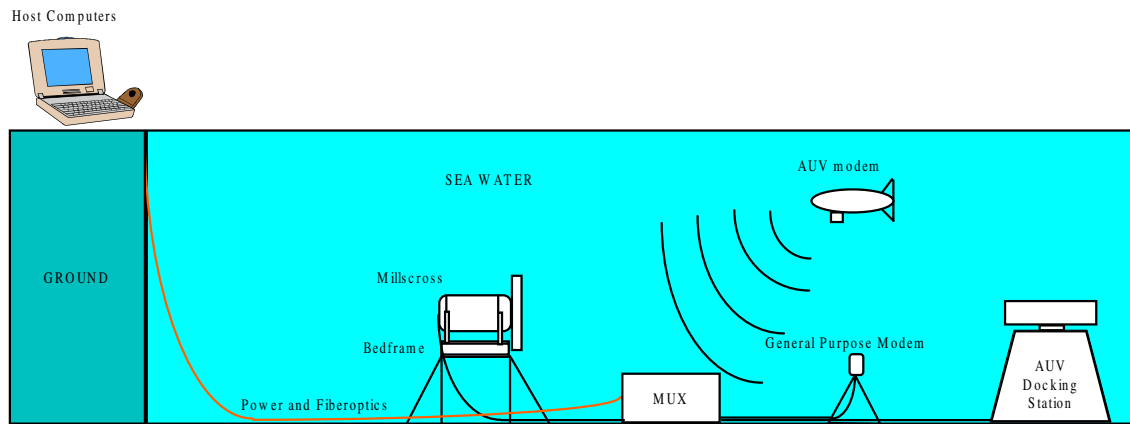
*Table 1. GPM and MillsCross Functions*

Modulation	Bandwidth	Burst Rate	Distance	Sea State	Doppler	Target Bearing	Results
BPSK	4kHz	4,000 bps	1km-1.5km	1-2', 4-6'	5 to 50Hz	0 to +/- 60 deg.	Available
QPSK	4kHz	8,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	Available
OPSK	4kHz	12,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	
BPSK	8kHz	8,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	Available
QPSK	8kHz	16,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	
OPSK	8kHz	24,000 bps	1km-1.5km	1-2', 4-6'	5 to 50Hz	0 to +/- 60 deg.	
BPSK	16kHz	16,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	Available
QPSK	16kHz	32,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	
OPSK	16kHz	48,000 bps	1km-1.5km	1-2'	5 to 50Hz	0 to +/- 60 deg.	

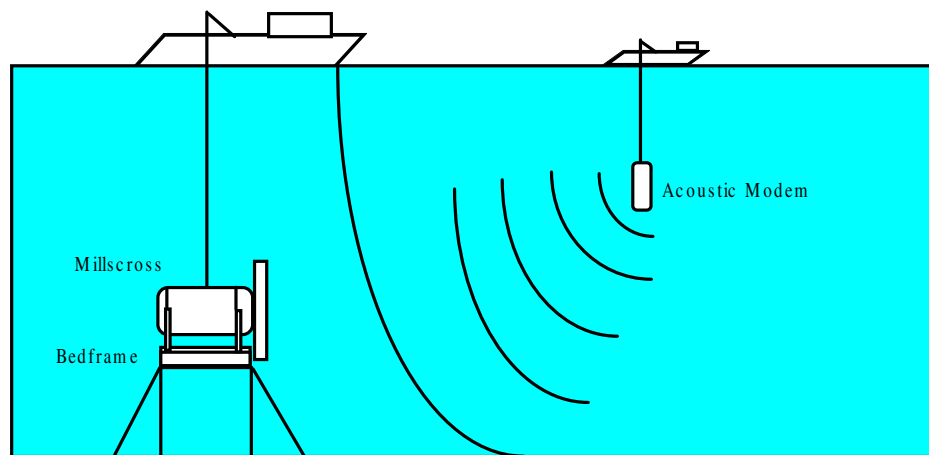
*Table 2.MillsCross Experiment and Analysis.*

PSK Type - Bandwidth (Hz)	BPSK - 4kHz	QPSK - 4kHz	BPSK - 8kHz	BPSK - 16kHz
Burst Data Rate (bps)	4000	8000	8000	16000
Burst Bit Error Rate (BER)	less than 0.1%	6%	6.50%	14.00%
Max Doppler Measured (Hz)	40	40	40	40
Equivalent Speed (m/s)	2.5	2.5	2.5	2.5
Training Overhead	10.00%	10.00%	12.50%	16.70%
Optimal BCH - Overhead	(255,247,1) 3.1%	(15,11,1) 26.7%	(15,11,1) 26.7%	(7,4,1) 42.8%
Final Packet Data Rate (bps)	3476	5064	4864	6480

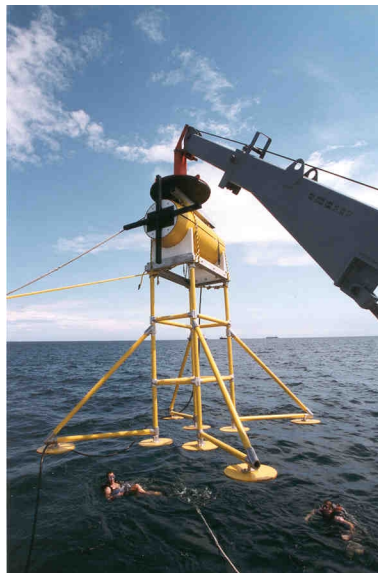
*Table 3. Measured Performance using Coherent Path Beamformer.*



### *1. Mechanical Setup for MUX Sea Test*

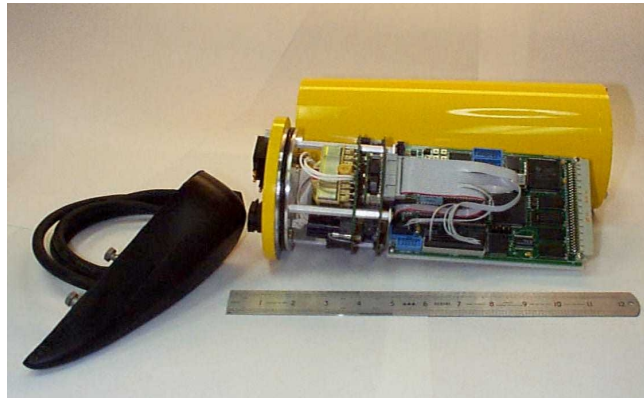


### *2. MillsCross and General Purpose Modem test using two boats.*

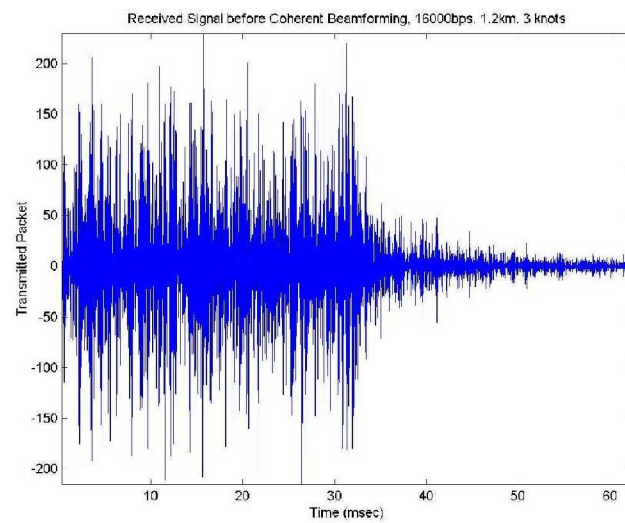


### *3. MillsCross on frame during at-sea operation.*

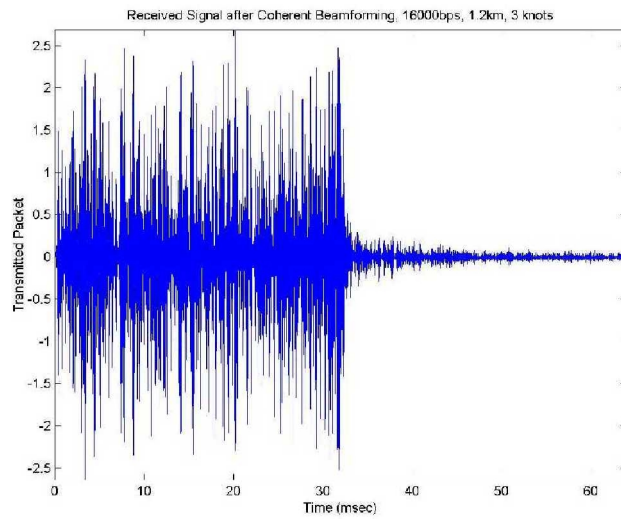




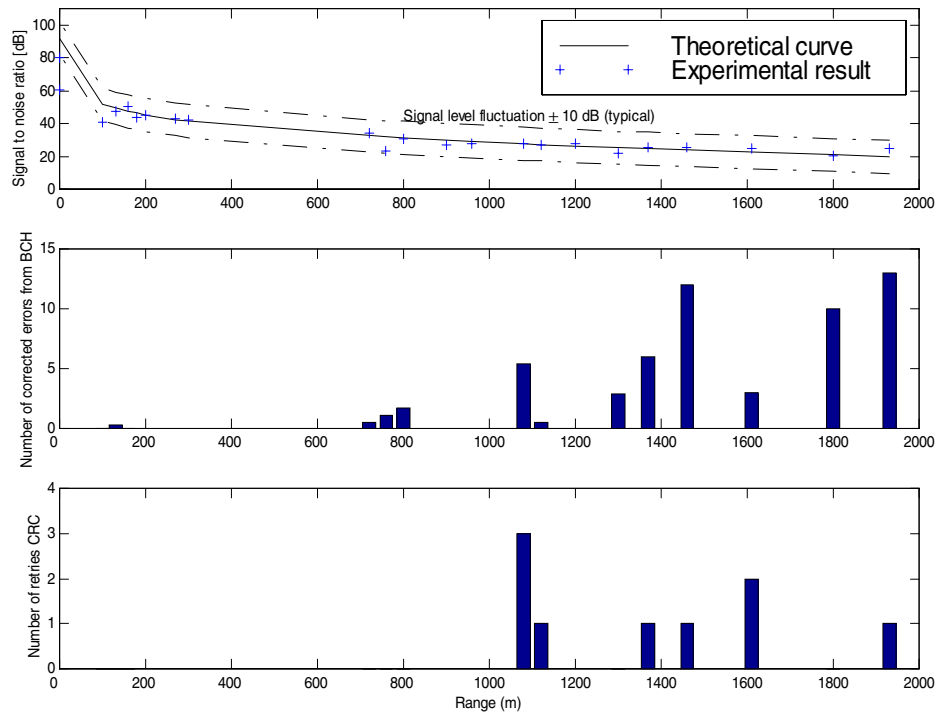
#### 4. *General Purpose/MFSK Modem.*



#### 5. *Example of Data Packet measured on a MillsCross Channel*



**6. Data Packet of Figure 5 after Coherent Path Beamforming**



**7. MFSK Acoustic Modem Performance vs. Range.**